Eos, Transactions, American Geophysical Union, Vol. 83, No. 25, 18 June 2002, Pages 273, 277-278

Recent Sediment Studies Refute Glen Canyon Dam Hypothesis

Recent studies of sedimentology, hydrology, and geomorphology indicate that releases from Glen Canyon Dam are continuing to erode sandbars and beaches in the Colorado River in Grand Canyon National Park, despite attempts to restore these resources. The current strategy for dam operations is based on the hypothesis that sand supplied by tributaries of the Colorado River downstream from the dam will accumulate in the channel during normal dam operations and remain available for restoration floods. Recent work has shown that this hypothesis is false, and that tributary sand inputs are exported downstream rapidly, typically within weeks or months under the current flow regime.

Restoration floods will be more effective at utilizing tributary sand inputs if floods are implemented before the new sand is lost downstream. Sand-transport rates through the canyon vary dramatically—even for constant water discharge—because tributary inputs cause substantial short-term enrichment in finer sand, resulting in enhanced transport (a result that is instructive for modelers in other river and marine settings). Although these new results contradict the Environmental Impact Statement (EIS) hypothesis, the Glen Canyon Adaptive Management Program was established precisely to help incorporate such scientific advances into management decision-making.

Background

Science has played an important role in managing releases from Glen Canyon Dam since at least 1983, and that role has increased as a result of the Glen Canyon Environmental Studies Program of the U.S. Bureau of Reclamation (1983–1996), the Grand Canyon Protection Act of 1992, the Environmental Impact Statement for Operation of Glen Canyon Dam [*U.S. Department of the Interior*, 1995], the 1996 controlled flood [*Webb et al.*, 1999], and the Secretary of the Interior's Record of Decision (ROD) for dam operations. The role of science in managing releases from the dam was also spurred by the creation of the Glen Canyon Dam Adaptive Management Program, which includes the Grand Canyon Monitoring and Research Center (GCMRC) [*U.S. Department of the Interior*, 1996]. The studies summarized here were funded by GCMRC; changes in dam operations recommended as a result of these recent studies are under review by the Adaptive Management Program.

Sandbars and banks are essential components of the Colorado River ecosystem and were distinctive features of the pre-dam river landscape. Emergent bars create terrestrial habitats for riparian vegetation and associated fauna, and they create areas of stagnant or low-velocity flow that may be utilized as habitat by endangered humpback chub (*Gila cypha*) and other native fish. Bars are also used by boaters and other park visitors. Sand deposits near and above the elevation of the pre-dam mean annual flood contain and help preserve archeological resources. As a result, restoration and maintenance of sand resources is one of several fundamental management objectives of the Glen Canyon Dam Adaptive Management Program.

Sandbars in the Grand Canyon are maintained by sand that is transported through the canyon. The high areas on these bars—those parts at elevations above peak power plant discharges—can be constructed only by flows that exceed such discharge (either natural or controlled floods). In the absence of floods, these high areas are eroded by low flows or canyon winds (Figure 1), or are rapidly colonized by vegetation. A flood can build bars by transferring sand from low areas to high areas if the channel contains sufficient sand. This benefit comes at the cost of sand reserves, however, because the same floods that build bars export substantial volumes of sand. Thus, a flood is a double-edged sword: high stage is indispensable for rebuilding bars, but the high discharge depletes sand resources rapidly. The challenge in managing sand resources is to maximize the transfer of sand to the bars while minimizing export of sand from the canyon. The approach to sandbar restoration in the ROD [*U.S. Department of the Interior*, 1996] is based on two hypotheses: first, much of the sand introduced by tributaries downstream of the dam can accumulate in the channel over multiple years during normal dam releases; and second, controlled floods can move that accumulated sand from the channel bed to bars, thereby rebuilding bars.

Recent Findings

Work conducted since the 1996 controlled flood has shown that the multi-year accumulation hypothesis on which the EIS was based is false, and that the bar-building hypothesis is only partially true. Topographic mapping [*Hazel et al.*, 1999] shows that the 1996 flood did increase the surface area of high-elevation sandbars (Figure 2), but more than half of the

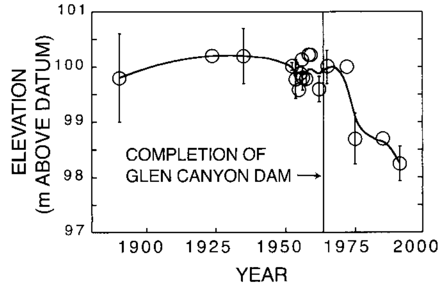

*Fig. 1. A decrease in elevation of the sandbar surface is seen at Jackass Creek camp located 37 km downstream of Glen Canyon Dam, following construction of the dam. Elevations were determined by examination of oblique and aerial photographs of the site and by field survey of the elevation and the former sand surface at its contact with large talus blocks. This graph shows the elevations near one prominent talus block that was inundated by the pre-dam mean annual flood, but has been only infrequently inundated since the dam was completed (*J.C. Schmidt and R.H. Webb, *pers. comm., 2001).*

sand deposited at higher elevations was cannibalized from the lower portions of the sandbars [*Schmidt*, 1999] rather than transferred from the channel bed as originally hypothesized.

Recent work also has shown that under dam operations imposed by the ROD, most newly input sand is exported relatively quickly (Figure 3) rather than being stored on the channel bed for long periods. Floods cannot take advantage of multiple years of sand accumulation, because substantial multi-year accumulation of sand does not occur. This conclusion has been relatively controversial, because it contradicts the hypothesis that formed the basis of the EIS, but the recent findings are persuasive.

Four kinds of data document the lack of multi-year accumulation:

- Measurements and calculations of input and output have shown that most fine sediment—defined here as clay, silt, and sand finer than 0.25 mm—delivered by tributaries is exported within a few months [*Topping et al.*, 2000a; *Topping et al.*, 2000b]. For example, field measurements show that sand delivered by floods on the Paria River in September 1999 was exported within 1–3 months (Figure 3).
- Changes in grain size of sediment on the riverbed also demonstrate rapid winnowing and export of tributary sand. The bed was measurably enriched in fine sediment from Paria floods in September 1998. By May 1999, however, the bed had been winnowed [*Topping et al.*, 2000b]. This sequence of fine-sediment enrichment followed by winnowing was repeated in 1999.

0096/3941/8325/273/$03.00.

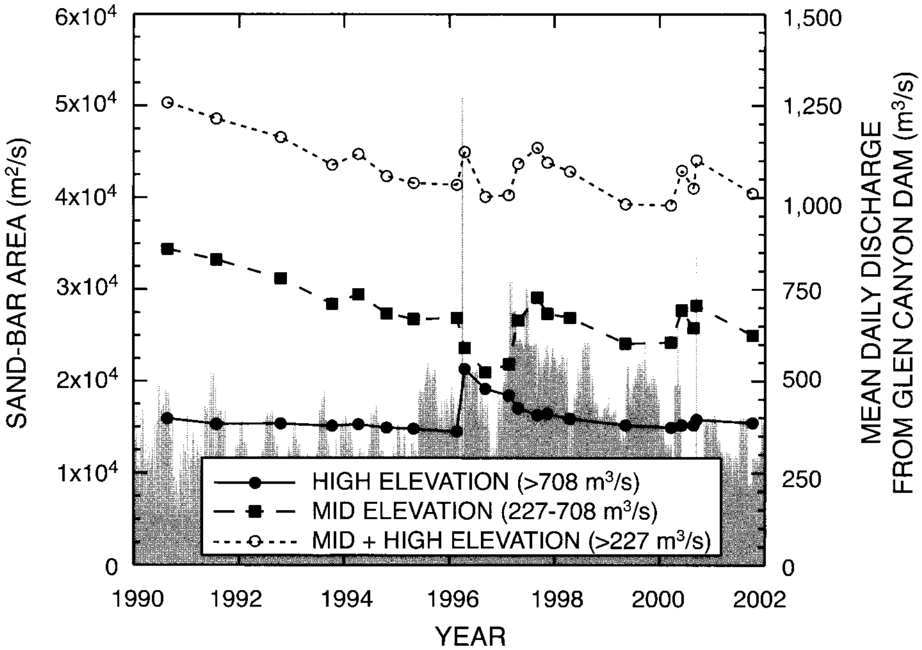

Fig. 2. Changes in sand-bar size (surface area) are shown at all 11 long-term Northern Arizona University study sites in the first 113 km downstream of Glen Canyon Dam. Area of bars exposed above water discharges of 227 m³/s decreased by 22% from 1991 to 1999. The 1996 flood resulted in a net transfer of sand from mid elevations to high elevations.

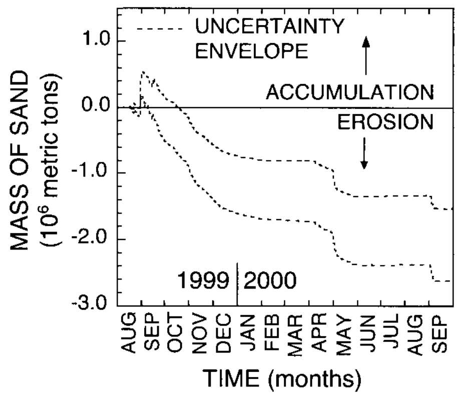

Fig. 3. Measured sand budget (input minus export) in the first 166 km downstream of Glen Canyon Dam, relative to the amount present on 15 August 1999. Upper and lower limits are calculated for hypothetical uncertainties of ±20% for inputs and ±10% for exports. Sand delivered by tributaries in August and September 1999, was exported within a few months.

• Geomorphic mapping from air photos and land surveys suggests that sandbar size decreased from 1984 to 2001. The controlled flood in 1996 increased high-elevation sandbar area to approximately the level seen in 1984, but this benefit was short-lived (Figure 2). Geomorphic mapping also indicates strong longitudinal gradients in sandbar deposition during the 1996 controlled flood and by a smaller flood in September 2000. Deposition was least near Lees Ferry and greatest downstream of the Little Colorado River [*Schmidt*, 1999; *Sondossi*, 2001]. Deposition increased downstream in response to increasing suspended sand concentrations; concentrations increased downstream because clear water from the dam encounters and erodes more sand as it flows downstream.

• Two sets of data document systematic net erosion since the early 1990s. First, repeated surveys of channel cross-sections [*M. Flynn and N. Hornewer*, pers. comm., 2001] found erosion at 55 of the 57 locations in their matching-date subset. Second, repeated surveys of 16 pools and adjacent deep eddies also show net erosion (J. Hazel and M. Kaplinski, pers. comm., 2002).

Sediment Export and Winnowing

A key requirement for devising a sediment-restoration strategy is knowing how long sand delivered by tributaries remains available for use by restoration floods. Inspection of rating curves that relate suspended-sand concentrations to water discharge indicates that post-dam concentrations are typically much lower than pre-dam concentrations for a given water discharge (Figure 4a); concentrations have decreased because the bed has coarsened [*Rubin and Topping*, 2001]. Even during the post-dam era, however, suspended sand concentrations can increase dramatically following inputs of fine sediment from tributaries and temporarily can be as high as the highest measured pre-dam concentrations (Figure 4a). These observations indicate that the rating curves shift quickly in response to changes in bed-sediment grain size, contradicting the EIS approach to calculating sand transport.

To quantify the export rate for a system with shifting rating curves, we hypothesize that suspended sand concentrations for average bed conditions are near the middle of the post-dam observed values, and that concentrations after a moderately large input are near the upper limit of observed values (Figure 4a).

The first half of a moderately large input is thus exported at a rate that decreases from the upper curve to the lower curve in Figure 4a. We used this approach to calculate the time required to transport one-half of a 500,000-metric ton input of tributary sand—the contribution of a typical, moderate, Paria River flood—past a gage located 139 km downstream. This calculated "half-life" of fine sand varies from a week or less for dam discharges above approximately 700–850 m³/s (25,000–30,000 ft³/s) to a year or more for discharges below 200–300 m³/s (7,000–10,000 ft³/s), as illustrated in Figure 4b. The time required to export the second half is greater than for the first half for a constant water discharge, because the second half is coarser, as a result of winnowing of the bed.

Optimizing Limited Sand Resources

For nearly 2 decades, managers have asked sediment transport researchers how flows might be adjusted to maximize sand resources in Grand Canyon. Recent results show that increases in sand abundance result from temporary storage following individual floods, rather than cumulative storage over multiple years; restoration of sediment resources is most likely to be achieved by implementing floods before new sand inputs are lost downstream. The authors recently outlined two possible approaches for exploiting sand inputs more effectively.

The first approach is to implement floods immediately following large tributary inputs. Large tributary floods that enrich the river with sand typically occur during late summer and early fall. Under the current operating plan for the dam, however, floods can be implemented only from January through July in years when specific criteria related to water storage in Lake Powell and forecasted runoffs are met [*Pulwarty and Melis*, 2001].

The second approach is to follow tributary sand-input events with low flows until flooding can be implemented. At dam releases that are typical of recent years, half of the sand introduced by a tributary flood can be exported within days or weeks (Figure 4b). Retention of sediment for more than a few months requires sustained dam releases that do not exceed approximately 200–300 m³/s (7,000–10,000 cfs), discharges that are near the lower limit of what is currently permitted.

Although the first approach might be most effective, it was not considered acceptable because of potential legal problems related to water use. The GCMRC did, however, formally propose that the second approach be implemented experimentally. In April 2002, the Adaptive Management Group endorsed this recommendation, which is being considered now by the U.S. Secretary of the Interior.

The Paria River is the sole substantial source of sand for the first 123 km downstream of Glen

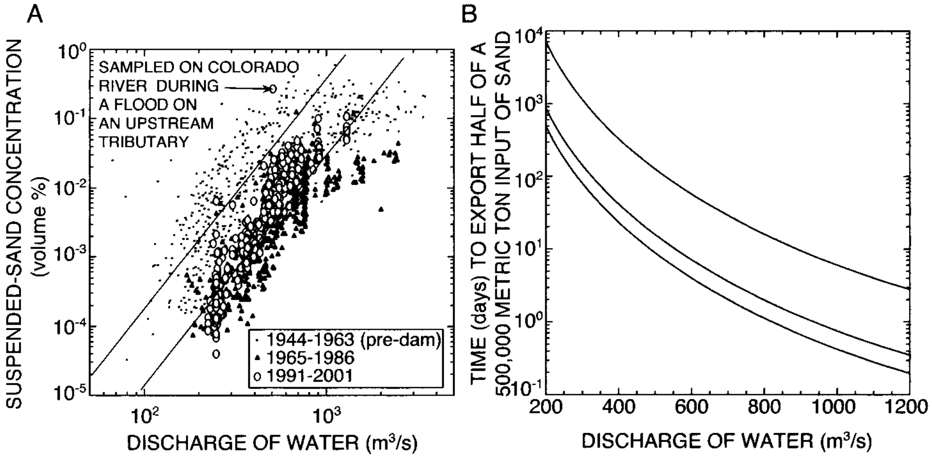

Fig. 4. (a) Concentration of suspended sand is shown as a function of water discharge in the Colorado River at the Grand Canyon Gage. Upper curve represents the rating curve for sediment-enriched, post-dam conditions, and lower curve is the rating curve for average post-dam conditions. These two curves were used to calculate the upper and lower limits in part b. (b) Calculated time to export one-half of a 500,000 metric ton input of tributary sand past the Grand Canyon Gage. The upper limit is calculated using the average suspended-sediment concentration for each specified discharge (lower curve in a); the lower limit is calculated for high concentrations of suspended sediment at each discharge (upper curve in a); the middle curve is calculated using concentrations that decrease through time from high values (during and immediately following tributary inputs) to mean concentrations (after half of the tributary sand has been exported). Under normal dam operations, one-half of a 500,000 metric ton input of tributary sand is exported within a few weeks or months.

Canyon Dam, and it provides only about 6% of the Colorado River's pre-dam average annual sand load at the upstream boundary of Grand Canyon National Park. This supply of sand may be insufficient to restore sediment resources in this critical upstream reach, which includes 98 km within the park. The other major supplier of sand, the Little Colorado River, enters downstream of this reach and historically has contributed a comparable amount of sand to the Paria. Since the mid-1980s, however, the Little Colorado River has contributed substantially less sand than the Paria. Because of the reduced sand supply, even the optimum dam operations may be ineffective in meeting management objectives for restoring sand bars. If so, other more effective alternatives are possible.

One such option—sediment augmentation—was eliminated during the environmental compliance process, partly because of the belief that sand bars could be restored merely by changing dam operations, and partly because of concerns about contamination of sediment upstream in Lake Powell [*Graf*, 1985]. Addition of sediment—continuously, seasonally, or perhaps only during floods—might offer greater operating flexibility and might therefore cost less than restrictions on dam operations. Without changes in dam operations or sand supply, however, it is unreasonable to hope to achieve the sand resource objectives identified by the Glen Canyon Dam Adaptive Management Program.

Authors

David M. Rubin, David J. Topping, John C. Schmidt, Joe Hazel, Matt Kaplinski, and *Theodore S. Melis*
For additional information, contact David M. Rubin, U.S. Geological Survey, Pacific Science Center, University of California, Santa Cruz, USA; E-mail: drubin@usgs.gov.

References

Graf, W. L., Mercury transport in stream sediments of the Colorado Plateau, *Ann. Assoc. Am. Geogr., 75*, 552–565, 1985.

Hazel, J. E., Jr., M. Kaplinski, R. Parnell, M. Manone, and A. Dale, Topographic and Bathymetric changes at thirty-three long-term study sites, in *The Controlled Flood in Grand Canyon*, Geophys. Monogr. Ser., 110, edited by R. H. Webb, J. C. Marzolf, and R. A. Valdez, pp. 161–184, AGU, Washington, D.C., 1999.

Pulwarty, R. S, and T. S. Melis, Climate extremes and adaptive management on the Colorado River: Lessons from the 1997-1998 ENSO event, *J. Environ. Manag., 63*, 307–324, 2001.

Rubin, D. M., and D. J. Topping, Quantifying the relative importance of flow regulation and grain-size regulation of suspended-sediment transport (∝) and tracking changes in grain size on the bed (β), *Water Resour. Res., 37*, 133–146, 2001.

Schmidt, J. C., Summary and synthesis of geomorphic studies conducted during the 1996 controlled flood in Grand Canyon, in *The Controlled Flood in Grand Canyon*, Geophys. Monogr. Ser., 110, edited by R. H. Webb, J. C. Schmidt, G. R. Marzolf, and R. A. Valdez, pp. 329–341, AGU, Washington, D.C., 1999.

Sondossi, H., Fine grained deposits of the Colorado River near Lees Ferry, Arizona, and their changes with time, M.S. thesis, Utah State University, Logan, 2001.

Topping, D. J., D. M. Rubin, and L. E. Vierra Jr., Colorado River sediment transport: Part 1: Natural sediment supply limitation and the influence of Glen Canyon Dam, *Water Resour. Res., 36*, 55–542, 2000a.

Topping, D. J., D. M. Rubin, J. M. Nelson, P. J. Kinzel III, and I. C. Corson, Colorado River sediment transport: Part 2: Systematic bed-elevation and grain-size effects of supply limitation, *Water Resour. Res., 36*, 543–570, 2000b.

U.S. Department of the Interior, Operation of Glen Canyon Dam Final Environmental Impact Statement, Bureau of Reclamation, Upper Colorado Region, 337 pp. plus appendices, Salt Lake City, March 1995.

U.S. Department of the Interior, Record of Decision, Operation of Glen Canyon Dam, Final Environmental Impact Statement, Office of the Secretary of Interior, 13 pp. plus attachments, Washington, D.C., October 1996.

Webb, R. H., J. C. Schmidt, G. R. Marzolf, and R. A. Valdez, (Eds.), The Controlled Flood in Grand Canyon, Geophys. Monogr. Ser., 110, 367 pp., AGU, Washington, D.C., 1999.